STEREO MISSION DESIGN IMPLEMENTATION

Jose J. Guzman, David W. Dunham, Peter J. Sharer, Jack W. Hunt, J. Courtney Ray, Hongxing S. Shapiro, Daniel A. Ossing, and John E. Eichstedt

The Johns Hopkins University Applied Physics Laboratory*

ABSTRACT

STEREO (Solar-TErestrial RElations Observatory) is the third mission in the Solar Terrestrial Probes program (STP) of the National Aeronautics and Space Administration (NASA) Science Mission Directorate Sun-Earth Connection theme. This paper describes the successful implementation (lunar swingby targeting) of the mission following the first phasing orbit to deployment into the heliocentric mission orbits following the two lunar swingbys. The STEREO Project had to make some interesting trajectory decisions in order to exploit opportunities to image a bright comet and an unusual lunar transit across the Sun.

INTRODUCTION

STEREO was successfully launched from PAD 17B at Cape Canaveral, Florida, with a Boeing Delta II rocket. The lift-off occurred on 2006 October 26 at 0:52:00.339 UT (14 minutes and 0.339 seconds into the 15 minute launch window). At about 1:14 UT, the Delta 3rd stage completed the injection of the STEREO stack into its highly elliptical orbit and the two separated from each other with a strong spring. Two minutes later, another spring separated the STEREO A and STEREO B spacecraft from each other and at 1:17 UT, all three objects emerged from the Earth's shadow into sunlight. At 1:21:39 UT, over half an hour before the spacecraft rose above the horizon at the Deep Space Network tracking station at Canberra, Australia, an amateur astronomer, Greg Roberts, near Cape Town, South Africa started taking images of the spacecraft; and, as far is known to STEREO personnel, he was the first and only person to observe the spacecraft optically after their injection.

The complex first orbit operations during the 10 days following launch, including two 0.2 m/s engineering test maneuvers and an 11.7 m/s apogee maneuver to raise perigee, preventing atmospheric re-entry, were described in a previous paper.[1] This paper describes in more detail the phasing orbits actually used by the mission and the planning for the maneuvers needed to target the lunar swingbys to accomplish the mission objectives. This is the detailed implementation of the maneuvers that were approximately planned in the studies for the launch window.[2] First, the basic plan for the phasing orbit maneuvers is given, including a description of guidelines and constraints. Next, the second orbit is described, especially the maneuvers used to target the first lunar swingby. The history of three more maneuvers performed by the Behind spacecraft to target the second lunar swingby is then told, along with other developments during this time, including Earth-based observations and images of the Moon and Comet McNaught taken by the spacecraft. The next section gives details of the phasing orbits and the maneuvers, documenting their characteristics and accuracy in a series of tables. A summary section describes the lunar transit imaged by Behind in February 2007 and discusses possible future options for the STEREO spacecraft. The first three authors constitute the STEREO Mission Design Team.

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* Mission Design Guidance and Control Group, Space Department, The Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, Maryland, 20723-6099, USA, e-mail jose.guzman@jhuapl.edu

PLAN FOR THE PHASING ORBIT MANEUVERS

Each STEREO spacecraft has twelve 4.5-Newton thrusters for performing ΔV and attitude adjustment (usually momentum dump) maneuvers, in three groups of four each, placed near the corners of the spacecraft box. The A group is on the bottom of the spacecraft, the -x side in the spacecraft body-fixed system, facing away from the Sun, to impart ΔV's in the +x (approximately sunward) direction. The B group is on the +z side to give ΔV's in the –z direction, and the C group is on the top (solar panel) side to provide ΔV's in the –x (anti-solar) direction, described in more detail elsewhere.[3]

Key events in the phasing orbits, and locations for actual and planned maneuvers, are shown in Figure 1. As described previously, two small engineering burns were performed in the first orbit, to assess the performance of the B and C thrusters, respectively. Some information about the A thrusters was obtained during the de-tumble maneuvers shortly after injection. The first engineering burn, E_1, was deemed most important since the B thrusters it tested would be used for the critical perigee raise maneuver near the first (A_1) apogee. The maneuvers near A_2 and P_2 (2^{nd} perigee) targeted the S_1 lunar swingby on December 15, 2006. As shown below, they were so accurate for Ahead that no further ΔV maneuvers were needed for that spacecraft. A small trajectory correction maneuver (**TCM**) was needed by Behind near the 4^{th} apogee (A_4) to improve the S_1 targeting well enough so that its S_2 lunar swingby would produce a heliocentric orbit drift rate within the design constrains. Shortly after the A_4 maneuver, the STEREO science team decided to change the aim point at the S_2 lunar swingby to achieve a transit of the Moon across the Sun as seen from the receding spacecraft on February 25, 2007. Two TCM's, one six days after the S_1 swingby and the other near A_5, were needed to accomplish that objective.

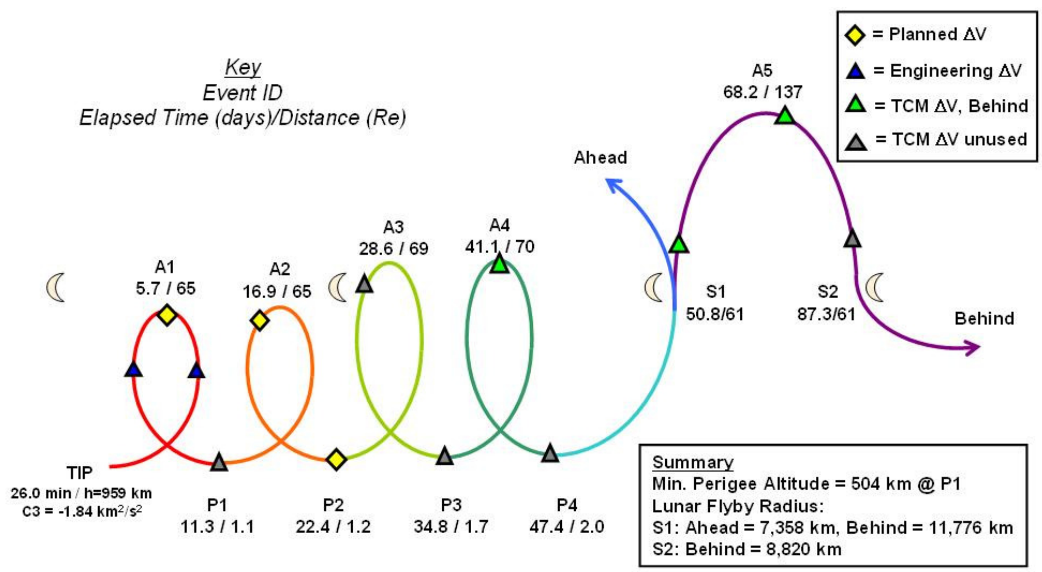

Figure 1 Schematic of STEREO's Phasing Orbits showing key events

Additional Deep Space Network (**DSN**) tracking for STEREO was scheduled for possible TCM's near the P_1, P_3, and P_4 perigees, and near A_3, but both the launch injection and previous ΔV's were accurate enough that no TCM's were needed at those locations. Maneuver design constraints are described below.

The +x-axis must be within 45° of the direction to the Sun, so that the spacecraft will have enough power from the solar panels. This means that if the ΔV is within 45° of the solar direction, the A thrusters must be used, while if it is within 45° of the anti-Sun direction, the C thrusters are used. Most of the time,

neither of these conditions are met, in which case the B thrusters are used, and the spacecraft is rolled around the z axis to minimize the +x direction to the Sun to meet the constraint.

Telemetry is needed during the maneuver to monitor its real-time progress, to make sure that the systems are operating properly, to allow an emergency abort command if needed, and to measure the change in the Doppler shift of the radio signal to see how well it matches the predicted shift. This means that the spacecraft must be within one of the DSN stations visibility periods, and at least half an hour from the start or end of the period. The start and end points are calculated either when the altitude of the spacecraft above the station's horizon is 10° or is at the station's mask limit (due to mountains or antenna pointing mechanical constraints), whichever is greater. This is important for perigee maneuvers when there is usually no DSN visibility for half an hour to an hour. During the phasing orbits, the distance to the Earth is relatively small, so that the hemispherical low gain antennas (**LGA**'s) on the +z and –z sides of the spacecraft can be used. Near the spacecraft "equator" 90° from the +z and –z directions, the received signal strength is low and spacecraft structures can block the line of sight. The blockage curves are shown in Figure 2, where the top (pole) is either +z (blue curve) or –z (orange curve) and –x is where the curves meet the equator to the left of center. In practice, rather than figure out the exact geometry, orientations were selected with the property that the Earth's direction from +z was always outside of the range of 75° to 105°. The –z LGA was preferred, since it was used during non-maneuver periods and there was a desire not to reconfigure to the +z LGA unless it was necessary. Also, when possible, the maneuver was designed to keep the angle greater than 110° to further improve the link margin and ensure no blockage in case the spacecraft deviated from the planned maneuver attitude.

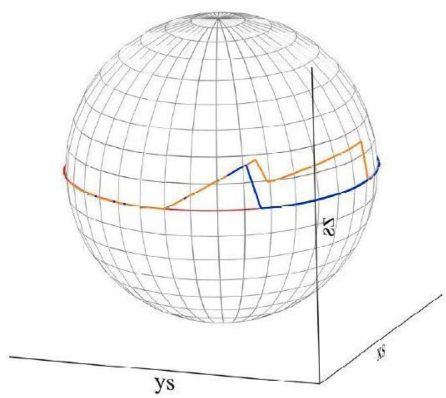

Figure 2 STEREO LGA masks for +z (blue) and –z (orange)

The maneuver must be in sunlight, so it can not be during an eclipse (there were eclipses at the first three perigees), and should be half an hour or more from the start and end of an eclipse, so that the spacecraft can have time to return to its nominal (+x) Sun-pointing attitude before the eclipse.

There must be an opportunity for a backup maneuver to achieve the same goals as the primary maneuver for a similar cost a day or more after the primary maneuver. In the case of maneuvers near perigee, the primary maneuver is performed far enough before perigee that there is DSN coverage and no eclipse, with the backup opportunity at the first chance after perigee. Details of the backup maneuver are computed in advance and commands to execute it are uploaded and stored on the spacecraft in a disabled state. If for any reason the primary burn fails to execute, a simple command can be sent to enable the backup maneuver to execute.

In addition, there are orbit design constraints that may limit the maneuver, to avoid a low perigee, etc., as described previously.[2] The maneuvers are designed to meet a specific goal, for example, the heliocentric drift rate from the Earth of +22.0°/year for Ahead and -22.0°/year for Behind, as described in more detail below.

SECOND ORBIT, TARGETING THE S_1 LUNAR SWINGBY

Since the launch occurred near the end of the daily launch window, large apoapsis maneuvers were required to adjust the out-of-plane component of the lunar B-plane for both spacecraft. In the launch window studies, these maneuvers were always performed after the 3rd apogee, and were called A_3+ maneuvers.[2] But with the large maneuvers that were now required near apogee, the Mission Design Team felt that it might be better to perform these maneuvers an orbit earlier, to allow A_3+ to be used to fine-tune the targeting, to clean up any errors of an earlier attempt. Calculations soon showed that there was no penalty or significant difference in placing the maneuver just after A_2 rather than after A_3. The team also considered splitting the burn between the two apogees to perform two possibly easier-to-manage smaller burns, but other team members on the STEREO project commented that this was not necessary and would complicate operations; the desire was to perform the least number of maneuvers to target the spacecraft to their desired heliocentric orbits. Thus, the Mission Design Team recommended, and the STEREO Project concurred, that these maneuvers be performed shortly after A_2 rather than A_3.

The original DSN tracking request did not include as much coverage near A_2 as desired for a maneuver, and a possible backup, but with some minimal swapping of DSN time with other projects, suitable coverage was arranged. The hope was that if the A_2+ maneuvers, as they were now called, were performed anywhere near as accurately as the A_1 maneuvers, there would be no need for maneuvers near A_3, and this was realized. The A_2+ maneuvers were scheduled for November 14 with a backup opportunity the next day. The maneuvers could have been performed equally well at any time during a long Goldstone DSN pass; the Mission Design Team recommended 14:00 UT, or 9 am local (Eastern Standard) time, for the Ahead maneuver, which was acceptable for the Operations Team. For the Behind spacecraft, the Mission Design Team recommended that the maneuver be executed one hour after Ahead's but the Operations Team requested at least two hours to be certain that there would be adequate time. As a result, a compromise to 16:00 UT for Behind, was made. The maneuvers for both spacecraft were very successful, as detailed below. The geometry of Ahead's A_2+ maneuver is shown in Figure 3. The geometry for Behind's A_2+ maneuver was similar, with +x Sun angle 35.2°, +z Earth angle 111.5°, but with a smaller ΔV of 28.4 m/s.

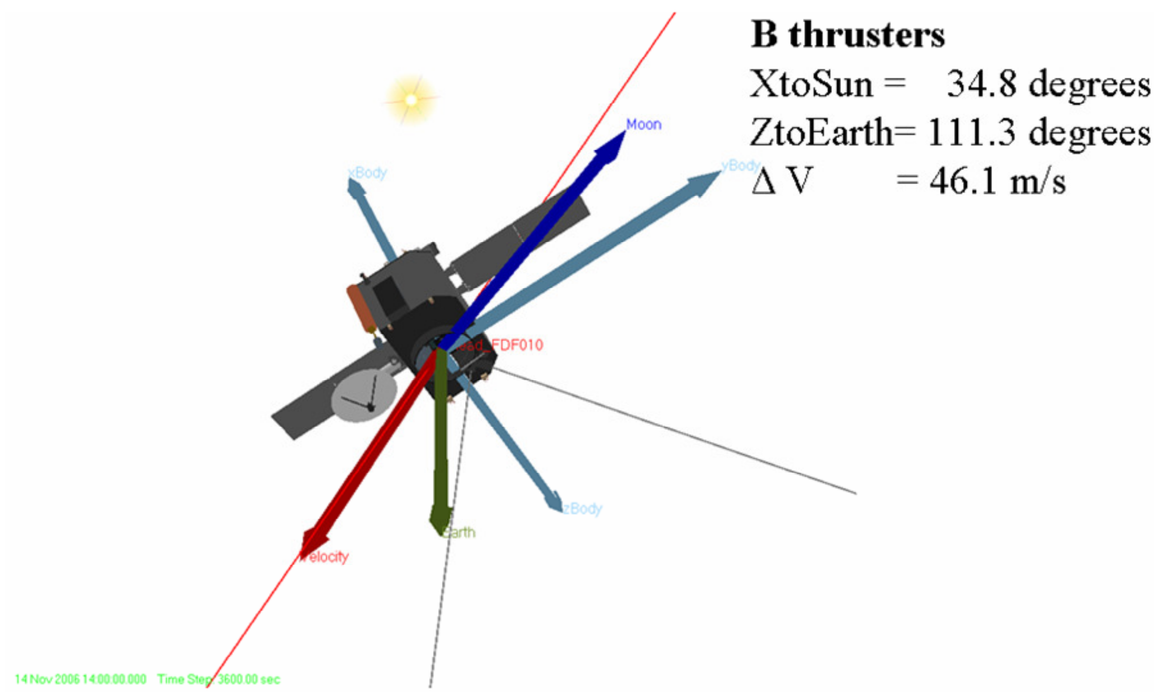

Figure 3 A_2+ ΔV Geometry for Ahead, November 14, 2006

Less than three days after the A_2+ maneuver, the P_2 maneuver had to be performed. The A_2+ and P_2 maneuvers were out-of-plane and in-plane (timing) maneuvers, respectively, needed to target the spacecraft to the proper points in the B-plane near the Moon at the first lunar swingby, S_1, on December 15th. The B-plane is shown in Figure 4, with drift rate contours plotted. The contours were generated by a large series of trajectory calculations, propagating the trajectory beyond the swingby for one year and evaluating the drift rate. The drift evaluation is performed if the trajectory is "heliocentric", that is, if the distance from the Earth is much greater than the Earth's sphere of influence. In this case a distance of about 2 million kilometers, comfortably beyond the L_1 and L_2 libration point distances of the Sun-Earth system, was used. If the trajectory is not "heliocentric" by this definition, it is still bound to the Earth (or has impacted the Moon or the Earth) and is shown as green.

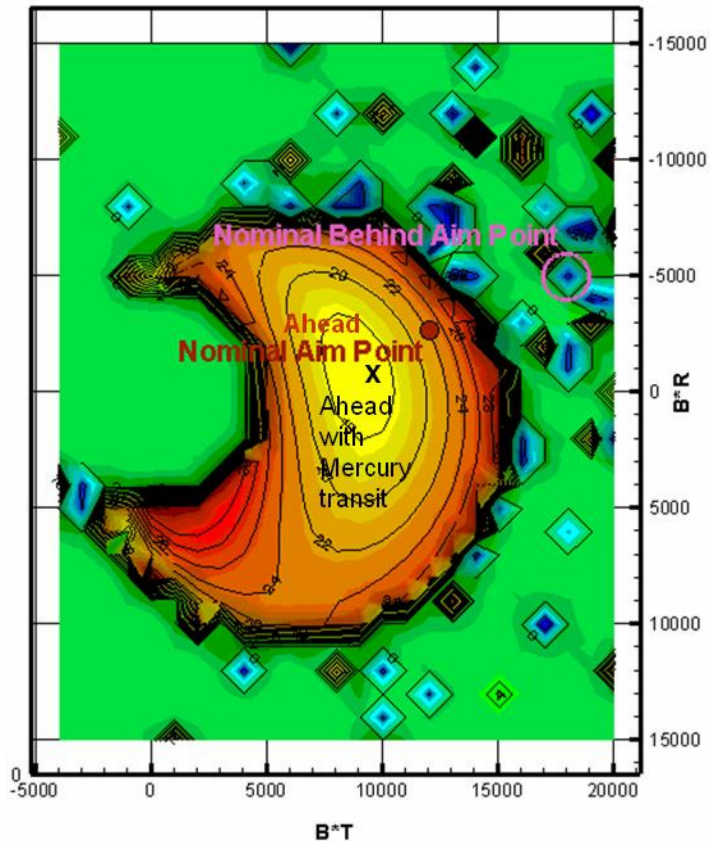

Figure 4 B-plane for the December 15, 2006 S_1 lunar swingby

The yellow to red areas show where positive drift rates are achieved; the 22°/year contour is the one desired for Ahead, and the red nominal aim point for it is on this curve. On November 9-10, 2006, a transit of Mercury was seen from the Earth, so some STEREO scientists asked if one of the STEREO spacecraft might be able to observe a Mercury transit. Propagating the nominal trajectories for several years in the future, Mercury was near its node on the ecliptic only on October 27, 2007 for Ahead, which was just over 2° from the Sun – Mercury direction at closest approach. We found that by decreasing the drift rate, it was possible to decrease the miss distance to 0 and have a Mercury transit. But an additional maneuver would be needed, and the STEREO Project concluded that Ahead observations of a Mercury transit would have no scientific value, so the nominal trajectory without the transit was maintained. There are also several small blue "islands" on the B-plane plot. These are places where, one or more months after the S_1 swingby, another close swingby of the Moon occurred, causing the spacecraft to escape with a negative drift rate. This is precisely what is desired for Behind, and its nominal aim point is indeed on one of these islands.

Now, the P_2 maneuver could not be performed at perigee since the trajectory was in the Earth's shadow there, and there was also no DSN contact at the time. Consequently, the maneuver was scheduled so that it would finish at least 30 minutes before entering the Earth's shadow. The geometry for the maneuver is shown in Figure 5. For Behind, the geometry was similar, with the +x Sun angle 24.0°, the +z Earth angle 123.2°, and a ΔV of 5.0 m/s. Using a 50-cm telescope, John Broughton obtained the CCD image of Ahead, showing as an 8th-magnitude streak, shown in Figure 6. More information about his observation, and the STEREO perigees, is at http://highorbits.jhuapl.edu/stereo.htm .

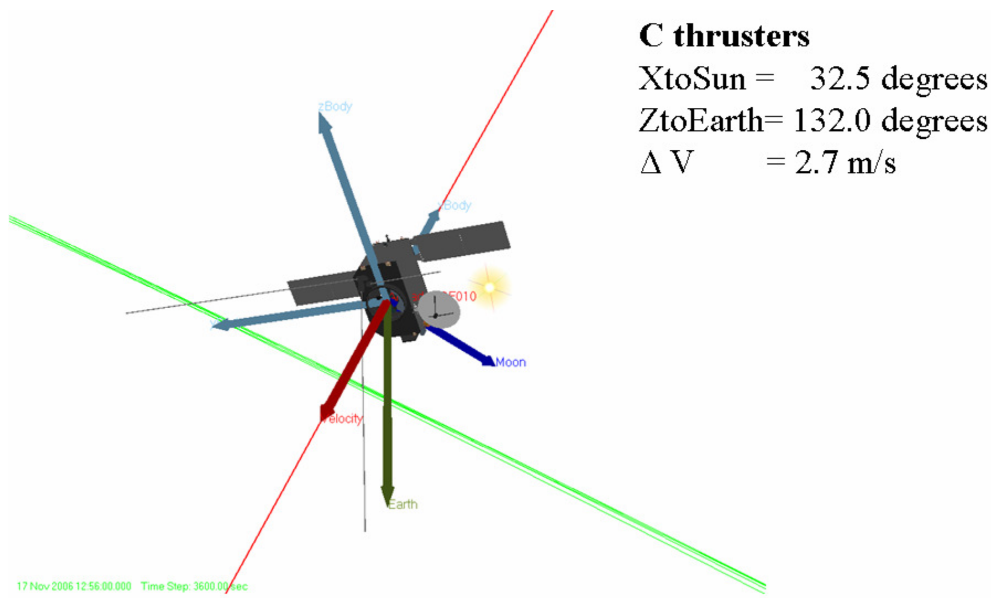

Figure 5 P_2 ΔV geometry for Ahead, November 17, 2006

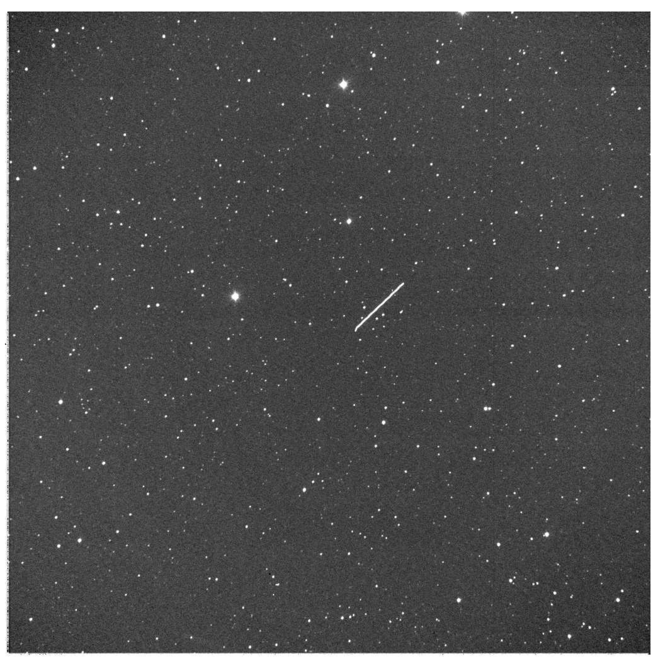

Figure 6 Image of Ahead near P_2 by John Broughton, Reedy Creek, Queensland, Australia

THE LAST PHASING ORBITS AND BEHIND'S LUNAR TRANSIT

The orbit determinations[4] after P_2 showed that the actual trajectories were close to the planned one, proving that the A_2+ and P_2 maneuvers had been performed accurately. For Ahead, the S_1 swingby was targeted accurately so that the drift rate would be +21.58°/year, well within the 2° tolerance from the planned +22.0°/year. No more ΔV maneuvers were needed, and none were executed, by Ahead after the P_2 maneuver. Behind also had an S_1 swingby that was accurate enough to already cause it to have an S_2 swingby, but the resulting drift rate was a few degrees from the -22.0°/year target; another small maneuver would be needed. The first thought was to perform it near P_3, but the trajectory was too sensitive there; the Guidance and Control team could not guarantee that the small maneuver there could be executed accurately enough to achieve the goal. Also, a maneuver on November 29th would require Operations personnel to work over the Thanksgiving holiday. It was found that a maneuver near A_4 in early December could easily correct Behind's drift rate; December 6th was selected since STEREO already had good DSN tracking coverage scheduled then.

An unfortunate aspect of Behind's trajectory is that it violated the solar distance constraints of Table 2 of Reference 2. Between the S_1 and S_2 lunar swingbys, with the Earth near perihelion, the minimum distance was violated much of the time, but this was just an artifact of the phasing orbits and there was no violation of the minimum distance in the heliocentric orbit following S_2. The solar distance constraint is scientific, based on the sizing of the occulting disk for the Sun Earth Connection Coronal and Heliospheric Investigation (**SECCHI**) coronagraph for covering the desired part of the Sun; there are no thermal or communications problems out to the A_5 apogee. Since science operations were not guaranteed until after the phasing orbits were completed, the minimum distance "violation" posed no problem. However, the aphelion of Behind's heliocentric orbit would cause the spacecraft to exceed the maximum solar distance of 1.089 AU for about a month each year. Again, this posed no thermal or communications problems and the science team did not have issues with it. However, an official waiver would be needed due to this constraint violation which the Project would prefer to avoid.

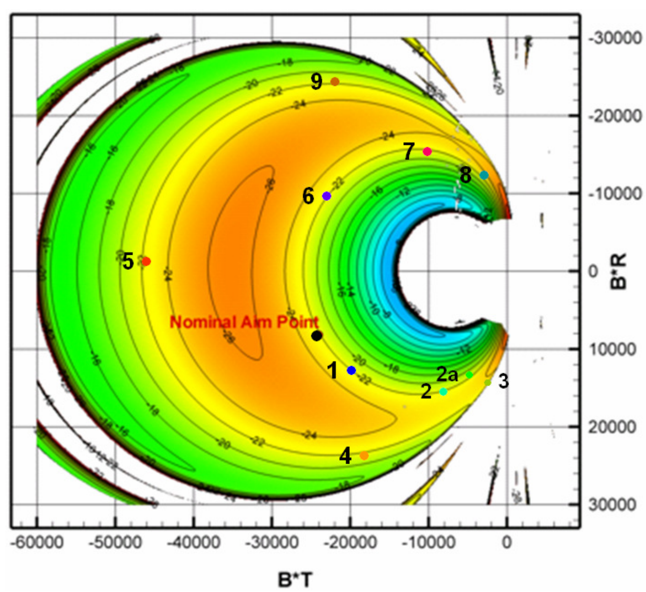

Figure 7 B-plane for the January 21, 2007 S_2 lunar swingby for Behind

The Mission Design Team decided to search for trajectories that might have lower aphelia. They constructed a drift rate B-plane plot for S_2 similar to that of Figure 4; the result is in Figure 7. Besides the nominal trajectory, nine trajectories were selected along the horseshoe-shaped -22.0°/yr for further study, numbered and color-coded in Figure 7. Trajectory 3 turned out to be on the outer side of the "horseshoe", while a point closer to the Moon still on the inside of the "horseshoe" was desired. A tenth trajectory, called "2a", was calculated to meet the goal. The resulting trajectories are shown in two views in Figures 8 and 9. Besides the -22.0°/yr "horseshoe" considered, there are also trajectories with the right drift rate along the outer dark edges of the negative drift rate region, but they are in a sensitive area difficult to calculate; they all dwell near the L_1 and L_2 libration points, interesting properties that in this case are not desired for operational and scientific reasons.

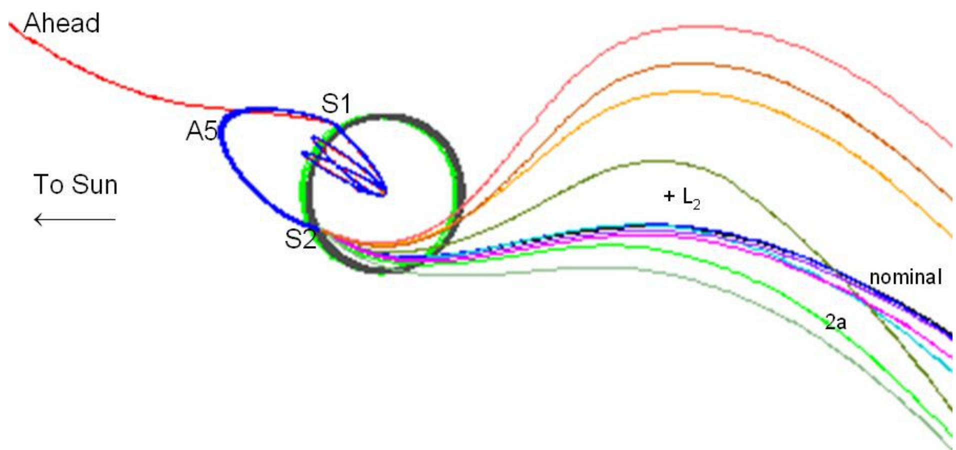

Figure 8 Rotating ecliptic-plane view of 11 trajectories with -22°/year drift rate

The upper trajectories of Figure 8, looping over the L_2 libration point, correspond to the more distant parts of the -22.0°/yr contour; these trajectories were not desired since the spacecraft would be on the "wrong" side of the spacecraft-Sun line for the first few months, hindering communications and scientific operations at a time when scientists were eager to prove the STEREO system's 3-dimensional solar imaging capabilities. So the closer, inner trajectories were examined in more detail. Trajectories 2a and 8 did not cross above L_2 and had lower aphelia distances than the nominal trajectory; in fact, they were less than the 1.089 AU constraint. These trajectories were tested for eclipses, and a long one by the Moon was found for 2a; it occurred on February 25, 2007 and is shown with an "x" in Figure 9. At first, this was thought to be a show stopper until it was realized that less than 5% of the Sun's disk would be eclipsed, a change in the thermal environment well within spacecraft tolerances. Rather than an eclipse, it was more like a big transit. When informed of the possibility, some of the SECCHI scientists became excited; the transit could provide an opportunity to make good measurements of stray light, to help calibrate other SECCHI images. At first, some scientists were worried that the higher inclination of the 2a trajectory to the ecliptic would cause some problems in correlating Behind's images with those by Ahead, although this would be a temporary problem that would go away as soon as the spacecraft drifted farther from the Earth. Operations did not want to change their already planned A_4 maneuver, so it was executed to target the nominal trajectory. Shortly after that, however, the STEREO scientists reached a consensus that the 2a trajectory with the transit was preferred. Work began on design of an "S_1+" maneuver six days after S_1, on December 21, to change the S_2 B-plane point to achieve the 2a trajectory.

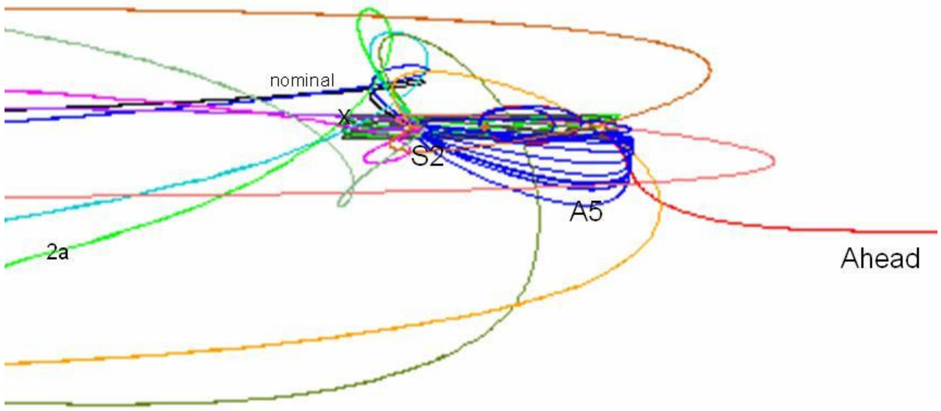

Figure 9 Rotating view towards the Sun of 11 trajectories with -22°/year drift rate; The lunar transit occurs at "x" on the "2a" trajectory

In the meantime, the spacecraft were headed towards its last (P_4) perigee and the Moon. Near P_4, the spacecraft would be higher than the previous perigees, and also since there was no eclipse, they would be visible from a wide area, including western North America and most of the Pacific Ocean. However, because of the distance, they would be relatively faint. The only known observation was made, again of Ahead, by Bill Keel of the Astronomy Department of the University of Alabama using remotely the SARA 0.9m telescope on Kitt Peak. The image and more information about it are at http://highorbits.jhuapl.edu/stereo.htm .

In Ahead's normal Sun-pointing attitude, momentum started to increase towards unacceptable limits; the Guidance and Control team designed a momentum dump to take care of this problem. It was successfully executed on December 13, a day after P_4. Shortly afterwards, since no more Ahead ΔV maneuvers were envisioned, the Heliospheric Imager (**HI**) door was opened and the spacecraft obtained an interesting series of images of the Moon just after the S_1 swingby, one example being shown in Fig. 10. The dark side of the nearly new (from Earth's perspective) Moon is seen illuminated by Earthshine; the CCD sensor was overwhelmed by the sunlit part of the Moon, only a small of it visible at the top of the figure.

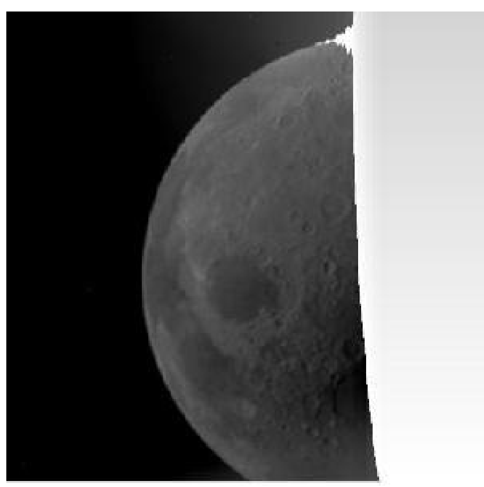

Figure 10 The Moon imaged with HI by Ahead just after S_1 on December 15, 2006

After S_1, on December 21, Behind performed the maneuver needed to change the S_2 B-plane point to the 2a trajectory. As can be seen in Figure 11, the size of the maneuver and its geometry were very similar to the first apogee (A_1) maneuver.

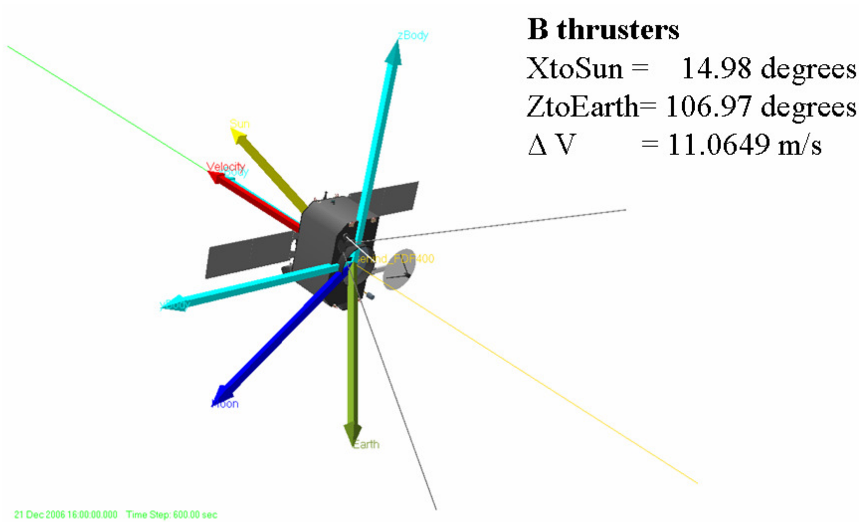

Figure 11 S_1+ ΔV geometry for Behind, December 21, 2006

Although the S_1+ maneuver was executed very accurately in both magnitude and direction, the post-S_1 orbit solutions had some instability; by four days after the maneuver, it was determined that the new trajectory would just barely miss the lunar transit. Another maneuver of 0.8 m/s, performed on 2007 January 8 a few days after the A_5 apogee, successfully targeted the lunar transit. But this was not known for a few days, during which time the STEREO scientists and Project anxiously awaited the opening of Behind's instrument doors. Finally on January 11th, the Mission Design Team concluded that the trajectory was good for the lunar transit and abandoned plans for any more maneuvers. Just in time, Behind's instrument doors were opened and immediately an impressive series of images of Comet McNaught, the brightest comet to appear in 30 years, were taken. One of the images is shown in Figure 12 where the comet's overexposed head, saturating the vertical lines of the CCD, is on the right. Venus is at the bottom on the left with a vertical saturation line not nearly as strong as McNaught's. Many background stars and the comet's impressive tail, showing much detailed structure, completes the interesting view.

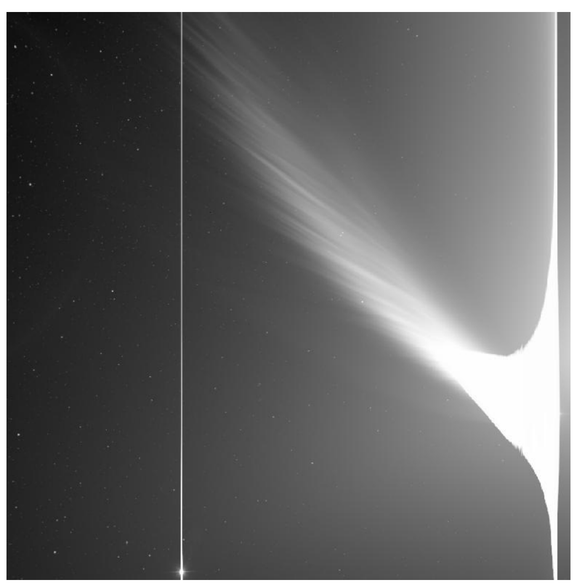

Figure 12 Comet McNaught imaged by Behind, January 2007

PHASING ORBIT TABLES AND MANEUVER RECONSTRUCTIONS

Information about key points in the phasing orbits of the STEREO spacecraft is given in Table 1. The number in the event name signifies the orbit, while A is for apogee, P is perigee, and S is a lunar swingby, numbered consecutively. Details of the eclipses that occurred during the first three perigees are given in Table 2, where STA is Ahead, STB is Behind, λ is longitude positive east of Greenwich, and ϕ is geodetic latitude, positive to the north.

Table 1 Phasing Orbits Key Events

EVENT	DATE	AHEAD		BEHIND	
		U.T.	h, km	U.T.	h, km
A_1	2006 Oct. 31	16:39	411,554	15:57	410,146
P_1	2006 Nov. 6	9:09	504	7:44	504
A_2	2006 Nov. 11	23:46	408,870	21:45	407,578
P_2	2006 Nov. 17	13:43	1,898	11:18	1,533
A_3	2006 Nov. 23	16:24	432,551	14:52	434,610
P_3	2006 Nov. 29	19:58	4,425	19:21	4,244
A_4	2006 Dec. 6	2:08	435,833	2:29	437,965
P_4	2006 Dec. 12	8:31	6,668	9:55	6,666
S_1*	2006 Dec. 15	21:28	7,358	21:03	11,776
A_5	2007 Jan. 2			6:02	867,843
S_2*	2007 Jan. 21			9:04	8,820

* Lunar swingby values in the h column are actually radii from the Moon's center

Table 2 Phasing Orbit Eclipses

EVENT, S/C	DATE	START				END			
		U.T.	h, km	λ, °	ϕ, °	U.T.	h, km	λ, °	ϕ, °
P_1, STA	2006 Oct. 31	8:59	1,665	+166	+27	9:20	2,208	-108	-15
P_1, STB		7:35	1,662	-173	+27	7:56	2,210	-87	-15
P_2, STA	2006 Nov. 17	13:36	2,506	+103	+28	13:57	3,506	+165	-17
P_2, STB		11:11	2,180	+137	+26	11:32	3,274	-155	-16
P_3, STA	2006 Nov. 29	19:56	4,448	+21	+14	20:15	5,944	+57	-9
P_3, STB		19:19	4,270	+30	+14	19:39	6,015	+71	-8
P_4, STA*	2006 Dec. 12	8:31	6,668	-175	+11				
P_4, STB*		9:55	6,666	+164	+11				

***** There was no eclipse at P_4, so the information for perigee is given in the "START" columns

Details of the ΔV maneuvers are given in Tables 3 and 4. They provide quantities described above, as well as the numbers of the pre- and post-ΔV trajectories, provided by the Flight Dynamics Facility[4] of the Goddard Space Flight Center, that were used for the maneuver reconstructions given in Table 5.

Table 3 Parameters of ΔV Maneuvers for Ahead

ΔV Name	Date UTC	Start UTC	ΔV mag. m/s	Thruster Group	X Sun deg.	Z Earth deg.	LGA	Pre ΔV FDF Orbit	Post ΔV FDF Orbit
E_1	2006 Oct. 28	13:30	0.196	B	20	119.29	Z-	STA476	STA553
A_1	2006 Oct. 30	18:00	11.709	B	15.32	110	Z-	STA553	STA582
E_2	2006 Nov. 02	18:00	0.202	C	33.42	118.44	Z-	STA582	STA002
A_2+	2006 Nov. 14	14:00	46.054	B	34.8	111.3	Z-	STA096	STA142
P_2	2006 Nov. 17	12:56	2.735	C	32.5	132	Z-	STA142	STA218

Table 4 Parameters of ΔV Maneuvers for Behind

ΔV Name	Date UTC	Start UTC	ΔV mag. m/s	Thruster Group	X Sun deg.	Z Earth deg.	LGA	Pre ΔV FDF Orbit	Post ΔV FDF Orbit
E_1	2006 Oct. 28	16:30	0.199	B	20	119.04	Z-	STB474	STB553
A_1	2006 Oct. 30	21:00	11.851	B	15.49	110	Z-	STB553	STB586
E_2	2006 Nov. 02	21:00	0.206	C	23.16	110.39	Z-	STB586	STB609
A_2+	2006 Nov. 14	16:00	28.422	B	35.2	111.5	Z-	STB102	STB136
P_2	2006 Nov. 17	10:00	4.95	C	24	123.2	Z-	STB136	STB225
A_4	2006 Dec. 06	20:00	0.205	B	0.45	61.33	Z+	STB262	STB313
S_1+	2006 Dec. 21	16:00	11.071	B	14.98	106.97	Z-	STB427	STB488
A_5+	2007 Jan. 08	19:00	0.791	B	27.7	107.6	Z-	STB544	STB599

In Table 5, the “actual” ΔV magnitudes, J2000 Earth equatorial right ascensions, and declinations (in the 3rd, 4th, and 5th columns, respectively) are calculated from a 6 degree of freedom adjustment of the initial position and the ΔV, using its observed duration, to match the post-maneuver state vector. The errors in magnitude (in m/s and percent) and pointing are formed by subtracting the actual values from the planned values given in the maneuver plan files, which were used by the Guidance and Control, and Operations Teams. The maneuver plans are deposited in the Stereo Data Server; more details, including ephemeris SPK SPICE files, are available upon request. Trajectories for both spacecraft starting at separation of the two spacecraft on October 26, 2006, are on the Jet Propulsion Laboratory’s “Horizons” ephemeris generator.

Table 5 ΔV Maneuver Reconstructions

Spacecraft	Maneuver	ΔV mag. (m/s)	ΔV RA deg	ΔV Dec deg	Error ΔV mag. (m/s)	% error in ΔV mag.	Pointing error (deg)
Ahead	E_1	0.196	-36.67	9.23	-3.85E-03	-1.924	2.56
	A_1	11.709	-46.35	29.04	-8.04E-03	-0.069	0.97
	E_2	0.201	8.04	2.09	8.97E-04	0.448	1.69
	A_2+	46.054	85.27	69.30	-3.66E-03	-0.008	0.36
	P_2	2.735	63.24	-11.77	2.69E-03	0.099	0.13
Behind	E_1	0.199	-36.56	6.84	-1.04E-03	-0.520	3.17
	A_1	11.650	-45.93	28.98	-9.49E-03	-0.081	0.89
	E_2	0.202	14.25	14.39	2.37E-03	1.184	0.68
	A_2+	28.422	84.93	68.65	9.85E-04	0.003	0.17
	P_2	4.950	56.20	-4.78	7.61E-03	0.154	0.09
	A_4	0.205	153.87	-25.04	4.16E-03	2.068	2.15
	S_1+	11.071	61.77	-47.05	5.78E-03	0.052	0.15
	A_5+	0.791	179.41	27.17	4.22E-03	0.537	0.64

SUMMARY AND STEREO'S FUTURE

STEREO was the first mission to use lunar swingbys to place two spacecraft, launched on one rocket, into very different (in this case, oppositely-directed) orbits. Some resulting images of Behind's lunar transit taken just over a month after the last swingby are shown in Figure 13. As detailed above, the maneuvers were performed extremely accurately. This combined with an accurate launch[1] have left the STEREO spacecraft with a generous supply of propellant, with about 60 m/sec ΔV capacity remaining.

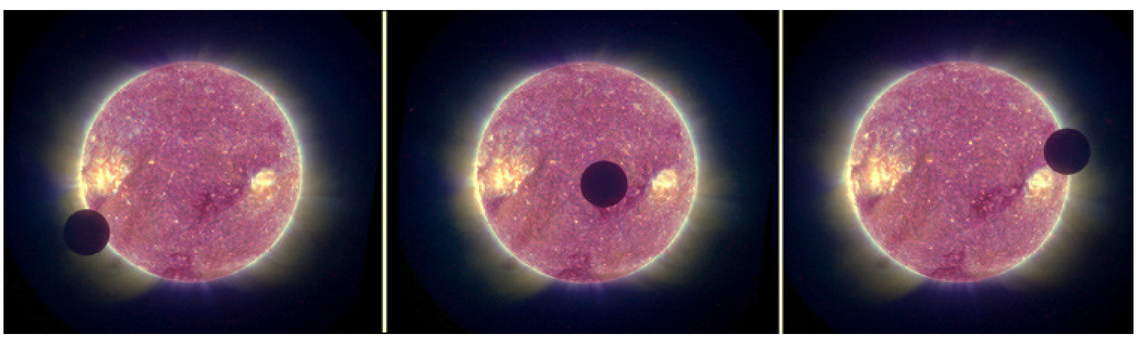

Figure 13 Lunar transit as observed by SECCHI on Behind, February 25, 2007

Some scientists would like to stop the STEREO spacecraft's drift near the L_4 and/or L_5 libration points of the Sun-Earth system, but to do that directly would require 600 m/s, about 10 times the remaining capacity. The additional maneuvers for Behind ended up targeting its drift rate to -22.000°/year, exactly the desired value. Last December, the Mission Design Team suggested modifying the maneuvers to achieve a -22.5°/year drift rate, which would add up to 360° and an Earth return in 2023, 16 years after launch. But with the current drift rates, Ahead's closest approach to Earth in 2023 will be 8.2 million km on August 20th while Behind's will be 10.0 million km on July 14th. Using approximately half of the remaining propellant could change the current drift rates to 22.5°/year. A possible trajectory with that drift rate is shown in

Figure 14, including an "S_3" lunar swingby that could put Behind in an L_2 halo orbit. With Earth and/or lunar swingbys in 2023, a significant change in the STEREO drift rate would be possible, if scientists of that time might want to do that, rather than just continue the mission with their already interesting trajectories.

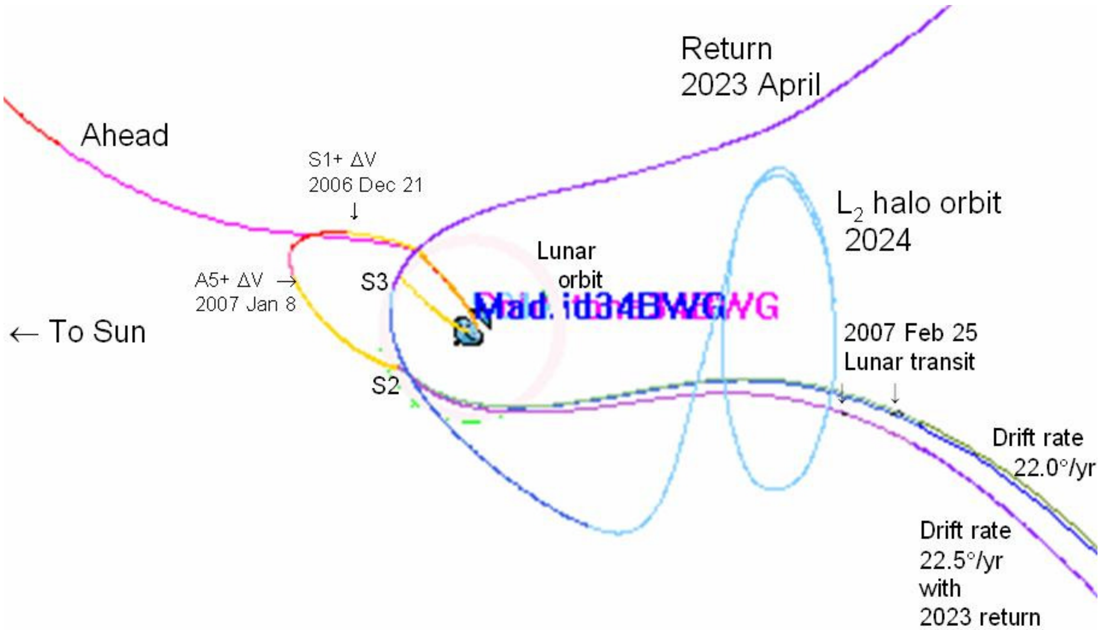

Figure 14 Behind Possible Return Trajectory in 2023

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